

# The $X(3872)$ at the TeVatron

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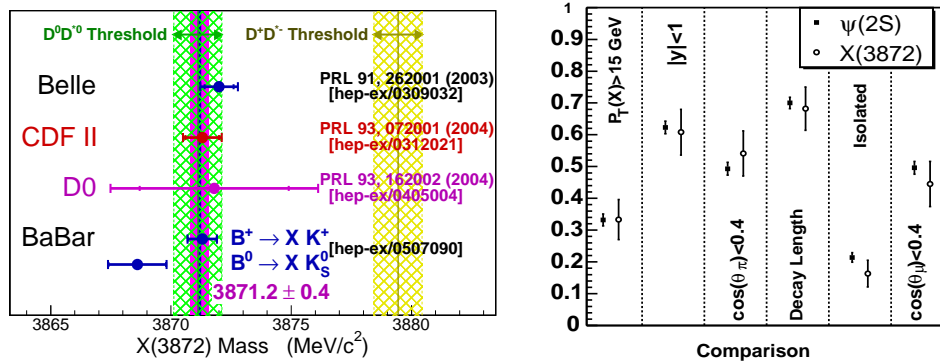
(Representing the CDF & DØ Collaborations)

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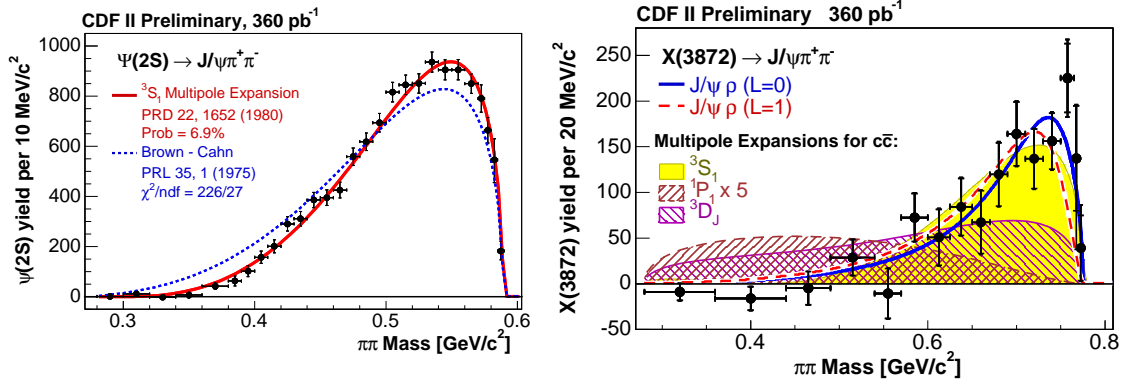
**Abstract.** I report results on the  $X(3872)$  from the Tevatron. Mass and other properties have been studied, with a focus on new results on the dipion mass spectrum in  $X \rightarrow J/\psi \pi^+ \pi^-$  decays. Dipions favor interpreting the decay as  $J/\psi \rho$ , implying even  $C$ -parity for the  $X$ . Modeling uncertainties do not allow distinguishing between  $S$ - and  $P$ -wave decays of the  $J/\psi$ - $\rho$  mode. Effects of  $\rho$ - $\omega$  interference in  $X$  decay are also introduced.

The charmonium-like  $X(3872)$  stands as a major spectroscopic puzzle. Its mass and what is known of its decays makes  $c\bar{c}$  assignments problematic. Exotic interpretations have been offered, notably that the  $X$  may be a  $D^0\bar{D}^{*0}$  “molecule” [1].

$X(3872) \rightarrow J/\psi \pi^+ \pi^-$  was confirmed by CDF [2] and DØ [3], and is copiously produced at Fermilab’s  $\bar{p}p$  collider—albeit with high backgrounds. Mass measurements are compared in Fig. 1, with an average of  $3871.2 \pm 0.4$  MeV/ $c^2$ . DØ studied other  $X$  properties by comparing the fractions of  $X$  yield in various types of subsamples to the corresponding fractions for the  $\psi(2S)$  [3]. The results for  $230 \text{ pb}^{-1}$  are summarized in Fig. 1, where the subsamples are the fraction of signal which have: **a)**  $p_T(J/\psi \pi \pi) > 15$  GeV, **b)**  $|y(J/\psi \pi \pi)| < 1$ , **c)**  $\cos(\theta_\pi) < 0.4$  ( $\pi$  helicity angle), **d)** proper decay length  $ct < 100 \mu\text{m}$ , **e)** no tracks with  $\Delta R < 0.5$  around the candidate, **f)**  $\cos(\theta_\mu) < 0.4$  ( $\mu$  helicity angle). In all cases the  $X$  results are compatible with those of the  $\psi(2S)$ . CDF used the



**FIGURE 1. LEFT:** Summary of  $X$ -mass measurements compared to the  $D^0\bar{D}^{*0}$  and  $D^+D^{*-}$  thresholds. **RIGHT:** DØ’s comparison of  $X$  production/decay properties to that of the  $\psi(2S)$  [3]. The fraction of the yield surviving the listed cut is plotted (see text for descriptions).



**FIGURE 2.** **LEFT:** The  $\psi(2S)$  dipion mass spectrum with fits of  $^3S_1$  multipole expansion and an older calculation of Brown and Cahn. **RIGHT:** The  $X(3872)$  dipion mass spectrum with fits of multipole expansion predictions for  $C$ -odd charmonia, and of  $X \rightarrow J/\psi \rho$  for  $L = 0$  and 1 using a relativistic Breit-Wigner with Blatt-Weisskopf factors ( $R_\rho = 0.3$  and  $R_X = 1.0$  fm).

proper decay length  $ct$  to quantify the fraction of  $X$ 's that come from  $b$ -hadrons, versus those that are promptly produced. Using  $220 \text{ pb}^{-1}$ , CDF finds the fraction of  $X$ 's from  $b$ -decays is  $16.1 \pm 4.9 \pm 2.0\%$ , in contrast to  $28.3 \pm 1.0 \pm 0.7\%$  of  $\psi(2S)$ 's [4]. The  $X$  fraction is somewhat lower than the  $\psi(2S)$ 's, but within  $\sim 2\sigma$ . From these perspectives the  $X$  is compatible with the  $\psi(2S)$ . The large  $X$ -production at the Tevatron is indicative to some of a charmonium character [5]. Naïvely one expects production of a fragile  $D^0\bar{D}^{*0}$  molecule, bound by an MeV or less, to be suppressed. It may, however, be sufficient to accommodate these features if the  $X$  merely has a significant  $c\bar{c}$  “core.”

Another property is the dipion mass spectrum. If the  $X$  has even  $C$ -parity, the dipions are (to lowest  $L$ ) in a  $1^{--}$  isovector state, and dominated by the  $\rho^0$ . An odd- $C$  state produces  $0^{++}$  dipions, for which QCD multipole expansion predictions exist for  $c\bar{c}$ .

CDF used  $360 \text{ pb}^{-1}$  ( $\sim 1.3\text{k}$   $X$ 's) to measure the  $\pi\pi$ -spectrum [6, 7]. The sample is divided into  $m_{\pi\pi}$  “slices” and fitted for  $X(3872)$  and  $\psi(2S)$  yields. After modest efficiency corrections, the spectra of Fig. 2 were obtained. The  $\psi(2S)$  is a good reference signal and is well modeled by multipole predictions [8]. Also in Fig. 2 are multipole fits to the  $X$  for the  $C$ -odd  $c\bar{c}$  states. The  $^1P_1$  and  $^3D_J$  fits are unacceptable. The  $^3S_1$  is an excellent fit to the  $X$ , but no  $^3S_1$   $c\bar{c}$  is available for assignment in this mass region.

Earlier this spring CDF provided  $J/\psi \rho$  fits using a simple non-relativistic Breit-Wigner sculpted by phase space [6]. Good agreement was obtained (36% probability). About the same time Belle released new dipion data fit with a more sophisticated  $\rho$  model [9], which included the effects of angular momentum  $L$  in the  $J/\psi$ - $\rho$  system. The phase-space factor of the  $J/\psi$  momentum in the  $X$  rest-frame,  $k^*$ , generalizes to  $(k^*)^{2L+1}$ , thereby turning off the mass spectrum at the upper kinematic limit ( $k^* \rightarrow 0$ ) faster for  $L = 1$  than for  $L = 0$ . Belle obtained a good fit for  $S$ -wave decay, but only a 0.1% probability for  $L = 1$ . Thus, the latter case was strongly disfavored, and in conjunction with angular information, Belle argued for a  $1^{++}$  assignment for the  $X$  [9]. The above CDF fit for  $J/\psi \rho$  was implicitly for  $L = 0$ . A CDF fit using Belle's  $L = 1$  model also yields 0.1% probability. The implication is, however, not robust.

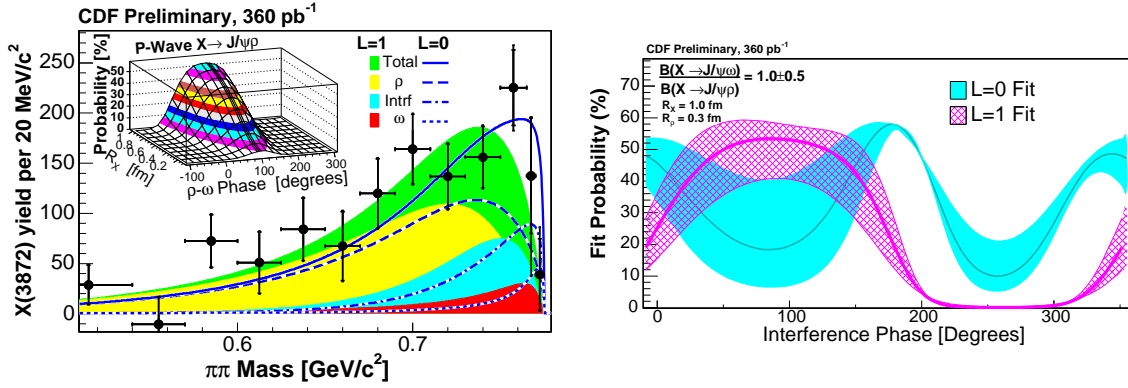
Breit-Wigner formulations are often modified by Blatt-Weisskopf form factors [10]. The centrifugal modification to  $(k^*)^{2L+1}$  tends to be too strong, and for  $L = 1$  it is multiplied by  $f_{1i}(k^*) \propto (1 + R_i^2 k^{*2})^{-\frac{1}{2}}$ , where  $R_i$  is a “radius” of meson- $i$ . Specifically, CDF’s  $J/\psi\rho$  model is:  $dN/dm_{\pi\pi} \propto (k^*)^{2L+1} f_{LX}^2(k^*) |B_\rho|^2$  for angular momentum  $L$ . The  $\rho$  propagator  $B_\rho \propto \sqrt{m_{\pi\pi}\Gamma_\rho(m_{\pi\pi})}/[m_\rho^2 - m_{\pi\pi}^2 - im_\rho\Gamma_\rho(m_{\pi\pi})]$ , where  $\Gamma_\rho(m_{\pi\pi}) = \Gamma_0 [q^*/q_0^*]^3 \times [m_\rho/m_{\pi\pi}] [f_{1\rho}(q^*)/f_{1\rho}(q_0^*)]^2$ ,  $q^*$  is the  $\pi$  momentum in the  $\pi\pi$  rest-frame, and  $q_0^* \equiv q^*(m_\rho)$ . The  $\rho$  parameters  $m_\rho$  and  $\Gamma_0$  are taken from the PDG. The  $L = 0$  factor is  $f_{0i}(x) = 1$ . The  $f_{1i}$  factors require two uncertain parameters,  $R_X$  and  $R_\rho$ . For light mesons, like the  $\rho$ , values  $\sim 0.3$  fm are usually found, whereas for charm mesons larger radii  $\sim 1$  fm are often used [11]. Choosing these values for  $R_\rho$  and  $R_X$ , CDF obtains the fits in Fig. 2 (Right). The  $L = 0$  fit has an excellent probability of 55%. While the  $L = 1$  probability is not quantitatively as good, it is a respectable 7.7%. This  $P$ -wave fit is sensitive to the  $R_i$ ’s, whereby the probability can be increased by lowering  $R_\rho$  and/or raising  $R_X$ . We conclude that flexibility in the fit model can accommodate either  $L$ .

Other modeling uncertainties may arise, for example, the effects of  $\rho$ - $\omega$  interference. Belle reported  $X \rightarrow J/\psi \pi^+ \pi^- \pi^0$ , and interprets it as decay via a virtual  $\omega$ . As such, they find the ratio of  $J/\psi\omega$  to  $J/\psi\rho$  branching ratios  $\mathcal{R}_{3/2}$  is  $1.0 \pm 0.5$  [12]. Although  $\omega \rightarrow \pi^+ \pi^-$  is nominally negligible here, its interference effects may not be.

$dN_{2\pi}/dm_{\pi\pi}$  is generalized by replacing  $|B_\rho|^2$  with  $|A_\rho B_\rho + e^{i\phi} A_\omega B_{\omega 2\pi}|^2$  where  $A_\rho$  and  $A_\omega$  are  $X$ -decay amplitudes via  $\rho$  and  $\omega$ , and  $\phi$  is the relative phase. The form for  $B_{\omega 2\pi}$  is identical to  $B_\rho$  except  $\rho$  quantities are replaced by  $\omega$  ones, including the  $\omega \rightarrow \pi\pi$  branching ratio. The ratio  $|A_\omega/A_\rho|$  is established by the relationship between  $\mathcal{R}_{3/2}$  and the integrals of  $dN_{2\pi}/dm_{\pi\pi}$  and  $dN_{3\pi}/dm_{3\pi}$  for  $X \rightarrow J/\psi \pi^+ \pi^- \pi^0$ , where the latter is  $\propto |A_\omega B_{\omega 3\pi}|^2$ . The  $B_{\omega 3\pi}$  follows  $B_{\omega 2\pi}$  except the numerator contains  $\Gamma_{\omega 3\pi}(m)$ . While  $\Gamma_{\omega 2\pi}(m)$  follows  $\Gamma_\rho(m)$ , a different form for  $\Gamma_{\omega 3\pi}(m)$  is adapted from the SND experiment studying  $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$  [13]. They model  $\omega \rightarrow \pi^+ \pi^- \pi^0$  as virtual  $\rho\pi$  decays and use the  $\omega$  matrix-element  $|\vec{q}_{\pi^+} \times \vec{q}_{\pi^-}|^2$ , where  $\vec{q}_{\pi^\pm}$  are  $\pi^\pm$  momenta.

The integral of  $dN_{2\pi}/dm_{\pi\pi}$  depends upon the phase, which is *a priori* unknown. As an illustration,  $|A_\omega/A_\rho|$  is determined assuming that  $\phi$  arises completely from  $\rho$ - $\omega$  mixing, i.e.  $\phi = 95^\circ$  [14]. The  $dN_{2\pi}/dm_{2\pi}$  decomposes into three parts: “pure”  $\rho$  and  $\omega$  terms, and an interference cross-term. In this model with  $\mathcal{R}_{3/2} = 1.0$ , these fractions are, respectively, 71.0, 6.2, and 22.8% for  $S$ -wave decay, and 67.4, 8.7, 23.9% for  $P$ -wave. Fits with these fractions imposed are shown in Fig. 3 (Left). The  $S$ -wave probability has declined as the model peaks too much at high mass, but is still very good at 19%. Increasing the amount of high masses with interference improves the  $P$ -wave fit to 53%. The  $L = 1$  fit is sensitive to  $\phi$  and  $R_X$  as is seen in the inset of Fig. 3. The dependence on  $R_\rho$  is relatively weak for both  $L$ . The overall picture from these fits is insensitive to the  $\pm 1\sigma$  span of  $\mathcal{R}_{3/2}$ , as is seen in Fig. 3 (Right).

In summary, properties of  $X(3872) \rightarrow J/\psi \pi^+ \pi^-$  studied at the Tevatron are quite similar to those of the  $\psi(2S)$ . There is no viable  $C$ -odd charmonium assignment according to QCD multipole expansion fits to the  $\pi\pi$ -mass spectrum. Decay to  $J/\psi\rho$  provides good fits, irrespective of the  $c\bar{c}$  structure. This implies the  $X$  is  $C$ -even, in-line with Belle’s report of  $X \rightarrow J/\psi\gamma$  [12]. The effects of  $\rho$ - $\omega$  interference are introduced, and can be quite important. This type of  $\rho$ - $\omega$  modeling highlights that  $\mathcal{R}_{3/2} \sim 1$  implies



**FIGURE 3. LEFT:** Blow-up of the dipion spectrum with  $J/\psi\rho$  fits for  $L = 0$  (lines) and 1 (shaded) including  $\rho$ - $\omega$  interference with  $95^\circ$  phase and sub-components set by  $\mathcal{R}_{3/2} = 1.0$ . The decomposition into  $\rho$ , interference, and  $\omega$  terms is given. The inset shows  $L = 1$  fit probabilities as a function of  $\phi$  and  $R_X$  in 5% contours. **RIGHT:**  $J/\psi\rho$  fit probabilities for  $L = 0$  (shaded) and 1 (hatched) as a function of phase. The bands span the  $\pm 1\sigma$  range of  $\mathcal{R}_{3/2}$ .

the *intrinsic* amplitude for  $X \rightarrow J/\psi\rho$  is actually significantly suppressed relative to  $J/\psi\omega$  by virtue of the much greater phase space for  $J/\psi\rho$  decay over  $J/\psi\omega$ . Given the modeling uncertainties governing the tails of the Breit-Wigners—especially if  $\rho$ - $\omega$  interference is in play—the CDF spectrum can be well described by  $J/\psi\rho$  decay of either  $L = 0$  or 1: such as from  $C$ -even charmonia (e.g.  $1^{++}$  or  $2^{++}$ ) or by a  $1^{++}$  exotic as preferred for a  $D^0\bar{D}^{*0}$  molecule.

## REFERENCES

1. See for example: E.J. Eichten, K. Lane, and C. Quigg, hep-ph/0511179; and references therein.
2. D. Acosta *et al.* (CDF), Phys. Rev. Lett. **93**, 072001 (2004).
3. V.N. Abazov *et al.* (DØ), Phys. Rev. Lett. **93**, 162002 (2004).
4. G. Bauer (CDF), *DPF '04*, Riverside CA, 25-31 August 2004 [hep-ex/0409052].
5. K.-T. Chao, *2nd Workshop on Heavy Quarkonium*, FNAL, 20-22 Sep. 2003 [www.qwg.to.infn.it/WS-sep03/WS2talks/prod/chao.ppt]; G. Bauer, hep-ex/0505083; C. Meng, Y.-J. Gao, K.-T. Chao, hep-ph/0506222; M. Suzuki, hep-ph/0508258.
6. CDF Note 7570 (7 April 2005) [www-cdf.fnal.gov/physics/new/bottom.html]; S. Nahn, *APS/DPF Meeting*, Tampa FL, 16-19 April 2005 [www-cdf.fnal.gov/physics/talks\_transp/2005/aps\_bphys\_nahn.pdf]; A. Rakitin, Ph.D. Thesis, MIT (2005).
7. A. Abulencia *et al.* (CDF), FERMILAB-PUB-05/535-E, to be submitted to PRL.
8. T.M. Yan, Phys. Rev. D **22**, 1652 (1980); Y.-P. Kuang *et al.*, *ibid* D **37**, 1210 (1988).
9. S. Olsen (Belle), *APS/DPF Meeting*, Tampa FL, 16-19 April 2005 [belle.kek.jp/belle/talks/aps05/olsen.pdf]; K. Abe *et al.* (Belle), Lepton-Photon '05 [hep-ex/0505038].
10. J.M. Blatt and V.F. Weisskopf, *Theoretical Nuclear Physics*, John Wiley & Sons (1952).
11. For example: S. Kopp *et al.* (CLEO), Phys. Rev. D **63**, 092001 (2001); H. Albrecht *et al.* (ARGUS), Phys. Lett. B **308**, 435 (1993); D. Aston *et al.* (LASS), Nucl. Phys. B **296**, 493 (1988).
12. K. Abe *et al.* (Belle), Lepton-Photon '05, Uppsala, Sweden, 30 June-5 July 2005 [hep-ex/0505037].
13. M.N. Achasov *et al.* (SND), Phys. Rev. D **68**, 052006 (2003).
14.  $\Gamma_\rho/(m_\rho - m_\omega) \approx 2 \tan(95^\circ)$  [A.S. Goldhaber, G.C. Fox, and C. Quigg, Phys. Lett. B **30**, 249 (1969)].